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BEAM AND TORSION TESTS OF ALUMINUM-ALLOY 61S-T TUBING

By R. L. Moore and Marshall Holt
Aluminum Company of America

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SUMMARY

Tests were made to determine the effect of length and the effect of ratios of diameter to wall thickness upon the flexural and torsional moduli of failure of 61S-T aluminum-alloy tubing.

The moduli of failure in bending, as determined by tests in which the tubing was loaded on the neutral axis at the one-third points of the span, were found to bear an approximately linear relationship with diameter-thickness ratio and were practically independent of span within the limits investigated. Empirical equations are given describing the relations obtained.

The moduli of failure in torsion were found to be dependent upon length as well as upon diameter-thickness ratios. Empirical equations are given for predicting strengths within the range of plastic buckling. Within the elastic range, available torsion theories were found to be satisfactory.

INTRODUCTION

The tests described in this report were undertaken at the request of an aircraft manufacturer for data on the moduli of failure of aluminum-alloy 61S-T tubing in bending and torsion. In view of the increasing use of this alloy in aircraft construction there is a need for more information relative to its structural strength. An attempt has been made in this report to present data for 61S-T tubing paralleling that given in figures 5-6 and 5-7 of reference 1, for the other aluminum alloys commonly used in aircraft.

The object of this investigation was to determine the effect of length and the effect of ratio of diameter to wall thickness upon the flexural and torsional moduli of failure of 61S-T tubing.

MATERIAL

Two series of tests of 61S-T tubing were made: one of tubing having a nominal outside diameter of 2.00 inches and the other of tubing having an outside diameter of 1.32 inches. Each series consisted of tubes having ratios of outside diameter to thickness D/t of approximately 10, 20, 40, 60, and 80.

The mechanical properties of each item of tubing were determined by tensile, compressive, and shear tests of specimens of full cross section. These properties are summarized in table I and indicate that the material used was representative of normal commercial production. (See table 23 of reference 2.)

SPECIMENS AND METHODS OF TEST

The loading fixture used in the beam tests, which was designed and built at Aluminum Research Laboratories in 1937, is shown in figure 1. The specimens consisted of pieces of tubing of full cross section, 4 inches longer than the span. They were supported at the ends of the span and at the intermediate load points by snug-fitting yokes with knife-edge supports in the plane of the neutral axis. The end yokes were mounted on rollers in order to minimize restraint to movement of the ends accompanying the vertical deflections. Load was applied equally to the one-third points of the span through knife-edge bearings in the plane of the neutral axis.

The beam tests were made in an Amsler universal testing machine of 40,000-pound capacity. Intermediate load ranges of 1000, 2000, 4000, and 10,000 pounds were used in order to obtain the greatest precision and accuracy for the different sizes of tubing investigated.

The beam specimens are described in table II. A span equal to 20 times the diameter was used for all sizes of tubing, and spans of 10 and 6 times the diameter were also used for the 2-inch-diameter tubes having D/t ratios of 20, 40, and 60.

The torsion tests were made in an Amsler torsion machine of 1200-foot-pound capacity. Intermediate load ranges of 240, 400, and 800 foot-pounds, as well as the maximum load range, were used. The specimens consisted of full cross sections of tubing gripped over a 4-inch plugged length at each end. Table III gives the dimensions of the specimens and the ratios of diameter to thickness D/t and length to diameter L/D.

RESULTS AND DISCUSSION

Beam Tests

Table II gives the maximum loads supported by the tubing in the beam tests and the corresponding moduli of failure computed by the ordinary beam formula

$$F_b = \frac{Mc}{I} \tag{1}$$

where

F_b modulus of failure, pounds per square inch

M maximum bending moment under ultimate load, inch-pounds

c distance from neutral axis to extreme fiber, inches

I moment of inertia of cross section, inch^4

It will be seen from these data and from those shown in figure 2 that the moduli of failure in bending varied considerably with the ratios of diameter to thickness but that they were not sensitive to differences between spans of 6, 10, and 20 diameters. In the case of the thinnest-wall tubes, failures occurred suddenly by buckling of the tube walls; whereas, in the case of the thickest-wall tubes, failures occurred by plastic yielding accompanied by large deflections. In no case was there evidence of impending failure resulting from excessive tensile stresses.

Figure 2 also shows the relations found between tensile and compressive strengths and the D/t ratios of the tubes. The tensile strengths were practically constant for the tubings of different diameters and were independent of D/t; whereas the compressive strengths, of course, decreased as D/t increased. Computed compressive strengths within 10 percent of these test results are obtained for values of D/t from 20 to 80 by using the method given in reference 3, and the straight-line column curve for this material obtained by the method outlined in reference 4. The computed values are on the conservative side.

It is seen in figure 2 that the moduli of failure in bending were equal to or greater than the compressive strengths of the tubing for corresponding values of D/t. The maximum ratio of these stresses was 1.26, found for a D/t ratio of 40. In tests of some duralumin cylinders with D/t ratios greater than about 300 (reference 5), it was found that the ratio of the modulus of failure in bending to the compressive strength of the cylinders varied from 1.30 to 1.80. The duralumin cylinders failed at stresses in the elastic range; whereas the 61S-T tubes tested in this investigation failed at stresses above the elastic range.

Figure 3 shows a nondimensional plot of the data in which the coordinates are

$$\frac{1}{\delta_s} = \frac{E}{F_{cy}} \frac{t}{D} \tag{2}$$

and

$$\sigma_{rs} = \frac{F_b}{F_{cy}} \tag{3}$$

where

E modulus of elasticity, pounds per square inch

F_{cy} compressive yield strength, pounds per square inch

This method of plotting was proposed in connection with the analysis of results of similar tests on 17S-T round tubing (reference 6). The advantage of this nondimensional plot is that it is possible to include, on a rational basis, factors which are known to affect the modulus of failure in bending, such as the yield strength, the modulus of elasticity, and the proportions of the tubing. The data in figure 3 can be represented very well by the equation

$$\sigma_{rs} = 1.57 - \frac{1.7}{\frac{1}{\delta_s}} \qquad (4)$$

An expression for the modulus of failure of 61S-T tubing in terms of the compressive yield strength, the modulus of elasticity of the material, and D/t is obtained by substituting equations (2) and (3) in equation (4). The resulting expression is

$$F_b = 1.57\ F_{cy} - 1.7\ \frac{(F_{cy})^2}{E}\ \frac{D}{t} \qquad (5)$$

For the properties of the 61S-T tubing tested, equation (5) reduces to

$$F_b = 65{,}300 - 292\ \frac{D}{t} \qquad (6)$$

which is represented by the straight line shown with the data in figure 2. An equation for 61S-T tubing having any other value of compressive yield strength F_{cy} can be obtained by substituting this value in equation (5), provided, of course, that the material considered has about the same ratio of yield strength to ultimate strength as the tubing tested. If it is assumed that the minimum compressive yield strength is equal to the minimum specified tensile yield strength, which might be reasonable for this alloy on the basis of the values given in table I, the equation for 61S-T tubing that just meets the requirements for a minimum specified tensile yield strength of 35,000 pounds per square inch, according to Federal Specification WW-T-789, is

$$F_b = 55{,}000 - 208\ \frac{D}{t} \qquad (7)$$

The line represented by this equation corresponds to the design data given in figure 5-6 of reference 1, for 17S-T and 24S-T tubing. Figure 4 shows the effect of D/t upon the moduli of failure in bending for these three aluminum alloys, which have guaranteed minimum properties.

It should be borne in mind that the moduli of failure in bending here considered were obtained from tests in which equal loads were applied at the one-third points of the spans. Under other test conditions, such as center-point loading, slightly different values of modulus of failure would probably have been obtained.

Torsion Tests

Table III gives the maximum torques and the corresponding moduli of failure, or average shear stresses, for the tubes subjected to torsion tests. These values were computed by the formula

$$F_{st} = \frac{T}{2\pi r^2 t} \qquad (8)$$

where

F_{st} modulus of failure in torsion, pounds per square inch

T torque producing failure, inch-pounds

r mean radius, inches

Two types of action were obtained: one involving plastic buckling in which the moduli of failure were dependent mainly upon D/t; the other involving elastic buckling in which L/D as well as D/t was a significant factor. In the cases of plastic buckling, the moduli of failure developed were above the shear yield strengths of the material given in table I; in the cases of elastic buckling, the computed stresses were below these yield-strength values.

Figure 5 shows the results obtained by plotting t/D against ratios of moduli of failure in torsion to tensile strengths. This method of analyzing torsion test data for aluminum-alloy tubing was first used at the National Bureau of Standards (reference 7) and is helpful in illustrating the types of action involved. In view of the fact that only one test result for 61S-T tubing was obtained in the vicinity of the so-called range of plastic shear, the limits shown for this range are based largely upon the results of other torsion tests of aluminum-alloy tubing (reference 8). It has been found that the shear strength of the heat-treated alloys in torsion, which constitutes an upper limit for moduli of failure, may be taken conservatively at about 65 percent of the tensile strength. Although the transition between the ranges of plastic shear and plastic buckling has been selected arbitrarily at a value of t/D of 0.1 and there are some data which indicate this choice to be reasonable, there is, of course, no definite point marking the limits of the two types of action.

In the range of plastic buckling shown in figure 5 the relation between torsional modulus of failure, tensile strength, and t/D may be expressed approximately by the relation

$$2\frac{F_{st}}{F_{tu}} = 3.7\frac{t}{D} + 0.93 \tag{9}$$

where F_{tu} is the tensile strength in pounds per square inch. This empirical expression for 61S-T tubing differs from those developed for 17S-T, 24S-T, and 24S-RT tubing at the National Bureau of Standards (reference 7) and at Wright Field (reference 9) in that the slope of the corresponding straight line is less and the intercept on the theoretical curves for elastic buckling is higher than that found for these other aluminum alloys. The explanation for this difference may presumably be attributed to fundamental differences in the stress-strain characteristics of the materials. The ratio of the tensile yield strength to tensile strength for the 61S-T tubing used averaged 0.89, which is appreciably higher than the corresponding ratios for the other afore-mentioned aluminum alloys. For material having a yield strength equal to the tensile strength, it seems reasonable to believe that the straight line for the range of plastic buckling would become almost horizontal; that is, there would be no intermediate range between plastic shear, where the ultimate strength is the controlling factor, and the range of elastic buckling.

The transition between the range of plastic and elastic buckling with respect to t/D depends upon the length of tubing considered. The theoretical buckling curves shown in figure 5 were computed for an assumed condition of simply supported edges according to a solution developed by R. G. Sturm* and summarized in reference 10. Values of modulus of failure averaging about 7 percent higher would have been obtained had the torsion theory proposed by L. H. Donnell in reference 11 been used. Although the agreement between theoretical and observed moduli of failure in the elastic range is not especially good in some cases, the

*Thesis submitted to University of Nebraska in partial fulfillment of the requirements for the professional degree in Civil Engineering, June 1938.

results appear sufficiently close to warrant consideration of the length effect. In the reports by the Bureau of Standards and by Wright Field (references 7 and 9), Schwerin's theoretical solution for long tubes was used, which does not include length as a significant factor in the range of elastic buckling.

Figure 6 shows more clearly than figure 5 the relation found between moduli of failure in torsion and L/D. For tubes having values of D/t of 19.8 and 39.4, the length of specimen tested had no significant bearing upon ultimate strengths. For tubes having a value of D/t of 58.8 the effect of length was slightly noticeable, and for a value of D/t of 80.6 the length factor was quite significant. The test values for tubing with a value of D/t of 80.6 averaged about 12 percent below the theoretical curve for elastic action.

Figure 7 shows the relation found between moduli of failure in torsion and D/t for two series of tests involving different values of L/D. In the range of plastic buckling the empirical curve shown corresponds to the oblique straight line given in figure 5. The theoretical curves for elastic buckling were computed in the manner previously discussed. The fair agreement between computed and observed moduli of failure for the proportions of specimens used is believed to warrant the conclusion that the torsional strength of any size of 61S-T tube may be predicted with reasonable accuracy, provided that the ratio of tensile yield to ultimate strength is comparable to that for the material tested. In the range of plastic shear involving values of D/t less than about 10, the ultimate shear strength of the material in torsion may be assumed equal to 65 percent of the tensile strength. In the range of plastic buckling the empirical equation given in figure 7 requires only the substitution of a value for tensile strength F_{tu} to make it applicable to other 61S-T tubing or to other aluminum alloys having the same ratio of tensile yield to ultimate strength. Elastic buckling becomes critical whenever the stresses computed by the torsion theory, involving both D/t and L/D, are less than those determined by the equation proposed for plastic buckling.

Figure 8 shows the relation between D/t and moduli of failure in torsion for 24S-RT, 24S-T, and 17S-T tubing as indicated in figure 5-7 of reference 1 and corresponding data for 61S-T tubing having guaranteed minimum properties according to Federal Specification WW-T-789. Inasmuch as the ratio of tensile yield to ultimate strength for 61S-T meeting specification requirements is about 0.83, instead of 0.89 as found for the tubing tested, equation (9) is not strictly applicable. On the basis of results obtained from other torsion tests of aluminum-alloy tubing, however, in which it has been possible to investigate more thoroughly the effect upon torsional strength of the ratio of tensile yield strength to ultimate strength, the following equation for 61S-T tubing meeting specification requirements has been obtained

$$F_{st} = \frac{F_{tu}}{2} \left(5.9 \frac{t}{D} + 0.71\right) \qquad (10)$$

The curve for 61S-T tubing shown in figure 8 was determined from equation (10).

It should be pointed out in connection with figure 8 that the moduli of failure given in reference 1 are apparently extreme fiber stresses computed by the ordinary torsion formula for circular sections; whereas for the 61S-T tubing they are values computed on the assumption of a uniform distribution of shear stress at failure. The latter procedure was adopted because it was believed to approach more nearly the actual stress condition developed in a ductile material stressed above the elastic range. The difference between the two methods of computing moduli of failure does not become significant until relatively thick-wall tubes are considered. For a value of D/t of 20, for example, the difference in stresses is only 5 percent; for a value of D/t of 10, the difference is 10 percent. In the case of a solid round bar, having a value of D/t of 2, the modulus of failure defined as extreme fiber stress is 33 percent higher than the value obtained by assuming a uniform distribution of shear stress. It appears from figure 8 that the values of modulus of failure shown by the ANC-5 curves for values of D/t from 2 to 10 are not extreme fiber stresses but correspond rather to the assumption of uniform stress distribution made for the 61S-T tubing

CONCLUSIONS

The following conclusions have been drawn from the data and discussion presented in this report on beam and torsion tests of 61S-T aluminum-alloy tubing:

1. The material used in this investigation was representative of normal commercial production. The tensile and compressive yield strengths were approximately equal and averaged about 90 percent of the tensile strengths.

2. The moduli of failure in bending, as determined by tests in which the tubing was loaded on the neutral axis at the one-third points of the span, were found to bear an approximately linear relationship with diameter-thickness ratios and were practically independent of span within the limits investigated.

3. For diameter-thickness ratios between 10 and 80 the moduli of failure in bending exceeded, in every case, the compressive strength of the tubing obtained for specimens of slenderness ratio of 10. For diameter-thickness ratios less than 70 the moduli of failure also exceeded the tensile strength of the material.

4. For the tubing tested, which had a compressive yield strength equal to about 41,500 pounds per square inch, the moduli of failure in bending are approximated by the equation

$$F_b = 65{,}300 - 292\frac{D}{t} \qquad (6)$$

where

F_b modulus of failure in bending, pounds per square inch

D outside diameter, inches

t wall thickness, inches

For material that has a value of compressive yield strength equal to the minimum tensile yield strength of 61S-T, according to Federal Specification WW-T-789, values of moduli of failure in bending may be approximated by means of the equation

$$F_b = 55{,}000 - 208\frac{D}{t} \qquad (7)$$

5. The moduli of failure in torsion for the tubes which failed by plastic buckling for diameter-thickness ratios of 10, 20, and 40 at stresses above the shear yield strength of the material, were found to follow the empirical relation

$$F_{st} = \frac{F_{tu}}{2}\left(3.7\,\frac{t}{D} + 0.93\right) \qquad (9)$$

where

F_{st} modulus of failure in torsion, assuming uniform shear stress, pounds per square inch

F_{tu} tensile strength, pounds per square inch

Equation (9) appears applicable to other 61S-T tubing, provided that a ratio of tensile yield to ultimate strength of about 0.89, corresponding to that of the material tested, is obtained.

6. For 61S-T tubing that has properties just meeting specification requirements, for which the ratio of tensile yield to ultimate strength is equal to about 0.83, moduli of failure in torsion in the range of plastic buckling may be estimated from the relation

$$F_{st} = \frac{F_{tu}}{2}\left(5.9\,\frac{t}{D} + 0.71\right) \qquad (10)$$

7. The moduli of failure in torsion for the tubes that failed by elastic buckling, in which both diameter-thickness and length-diameter ratios were significant factors, were computed quite satisfactorily by available torsion theories. The limits of applicability of the buckling theories and the empirical equations for plastic buckling depend upon the length-diameter ratios of the tubing.

Aluminum Research Laboratories,
Aluminum Company of America,
New Kensington, Pa., May 22, 1942.

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TABLE I

MECHANICAL PROPERTIES OF MATERIAL USED FOR BEAM AND TORSION TESTS OF 61S-T ROUND TUBING

[Specimens of full cross section used; average modulus of elasticity in tension as determined with Martens mirror-type extensometer on 4-in. gage length, 10,000,000 lb/sq in.; average modulus of elasticity in shear as determined by Amsler troptometers on 16-in. gage length, 3,870,000 lb/sq in. Values from Federal Specification WW-T-789: tensile strength, 42,000 lb/sq in.; tensile yield strength, 35,000 lb/sq in.; elongation in 2 in. for wall thicknesses between 0.025 and 0.049 in., 8 percent; elongation in 2 in. for wall thicknesses between 0.050 and 0.259 in., 10 percent]

Nominal size (in.)		Yield strength (offset, 0.2 percent) (lb/sq in.)			Ultimate strength (lb/sq in.)		Elongation (percent)	
Outside diameter	Wall thickness	Tension	Compression	Shear	Tension	Compression[a]	in 2 in.	in 8 in.
1.32	0.016	40,500	(b)	(b)	45,000	40,800	10.0	8.3
	.023	38,000	(b)	(b)	43,000	39,000	17.0	11.4
	.033	38,500	41,000	22,000	43,800	41,900	19.0	11.9
	.066	39,800	42,300	22,800	46,200	46,300	18.5	12.0
	.132	39,700	41,000	22,500	45,200	52,700	22.0	12.3
2.00	.025	40,700	(b)	(b)	44,900	38,600	17.0	11.4
	.033	40,000	40,700	(b)	44,900	40,800	18.5	12.5
	.050	41,500	42,600	23,300	45,700	43,600	21.5	12.6
	.100	38,600	37,600	21,500	42,700	43,600	26.5	13.9
	.200	41,000	41,400	(c)	45,400	53,300	26.0	13.0

[a]Determined from specimens having a slenderness ratio of 10.
[b]Tube failed at a strain less than that defining the yield strength.
[c]Torsion machine capacity not sufficient to develop shear yield strength.

TABLE II

DESCRIPTION OF SPECIMENS AND RESULTS OF BEAM TESTS OF 61S-T TUBING

[Specimens tested as simply supported beams; load on neutral axis at one-third points of the spans]

Outside diameter, D (in.)	Wall thickness, t (in.)	D/t	Moment of inertia (in.^{4})	Span (diam)	Span (in.)	Maximum load (lb)	Modulus of failure[a] (lb/sq in.)
1.322	0.016	82.7	0.0140	20	26.0	197	40,310
1.322	.022	60.2	.0190	20	26.0	304	45,850
1.321	.033	40.0	.0277	20	26.0	512	52,915
1.329	.066	20.1	.0523	20	26.0	1067	58,730
1.319	.132	10.0	.0877	20	26.0	1893	61,660
2.002	.025	80.1	.0757	20	40.0	498	43,890
2.002	.033	60.7	.0990	20	40.0	720	48,530
1.998	.049	40.7	.1426	20	40.0	1172	54,740
1.998	.100	20.0	.2693	20	40.0	2215	54,720
2.001	.202	9.9	.4669	20	40.0	4400	62,860
2.002	.033	60.7	.0990	10	20.0	1467	49,440
1.998	.049	40.7	.1426	10	20.0	2356	55,010
1.998	.100	20.0	.2693	10	20.0	4400	54,410
2.002	.033	60.7	.0990	6	12.0	2449	49,490
1.998	.049	40.7	.1426	6	12.0	3975	55,680
1.998	.100	20.0	.2693	6	12.0	7445	55,250

[a]Computed bending stress in extreme fibers corresponding to maximum bending moment.

TABLE III. - DESCRIPTION OF SPECIMENS AND RESULTS OF

TORSION TESTS OF 61S-T TUBING

Outside diameter, D (in.)	Wall thickness, t (in.)	Length between grips, L (in.)	D/t	L/D	Maximum torque (ft-lb)	Modulus of failure[a] (lb/sq in.)
1.322	0.0164	7.5	80.6	5.7	70	19,100
		22.5	80.6	17.0	38	10,400
		36.5	80.6	27.6	34	9,300
1.325	.0225	7.5	58.8	5.7	93	18,600
		22.5	58.8	17.0	87	17,400
		36.5	58.8	27.6	76	15,200
1.321	.0335	7.5	39.4	5.7	165	22,700
		22.5	39.4	17.0	162	22,300
		36.5	39.4	27.6	160	22,000
1.318	.0665	7.5	19.8	5.7	346	25,400
		22.5	19.8	17.1	343	25,100
		36.5	19.8	27.7	354	25,900
1.319	.1320	22.5	10.0	17.1	697	28,600
2.000	.0248	23.0	80.6	11.5	195	15,400
2.001	.0330	23.0	60.6	11.5	339	20,200
1.998	.0495	23.0	40.4	11.5	589	23,900
1.996	.0995	23.0	20.1	11.5	1147	24,500

[a]Computed shear stress in mean fibers corresponding to maximum torque.

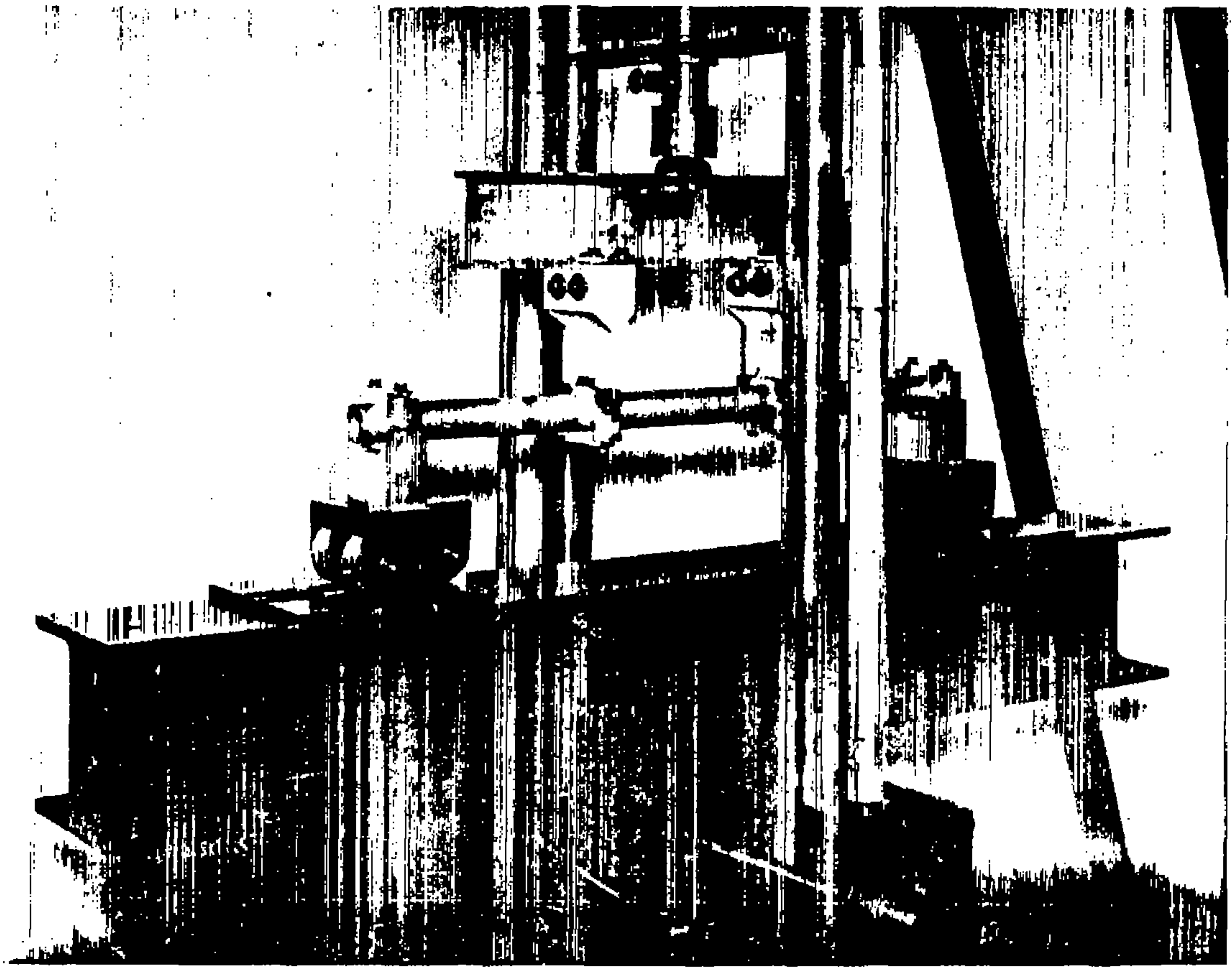

Figure 1.- Method of loading beam specimens on the neutral axis at the one-third points of the span.

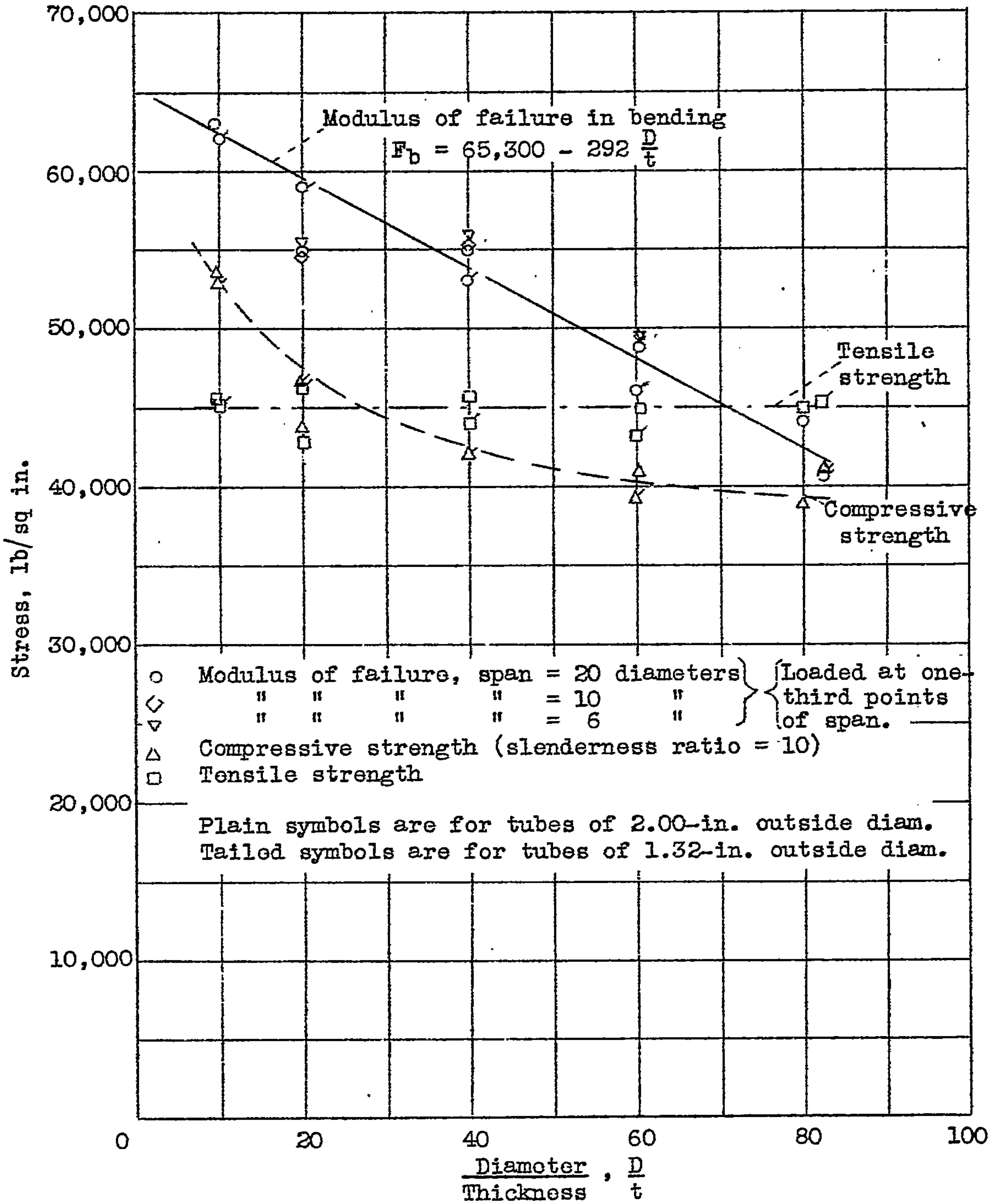

Figure 2.- Modulus of failure in bending and the mechanical properties of 61S-T round tubing.
Beams loaded at one-third points of span

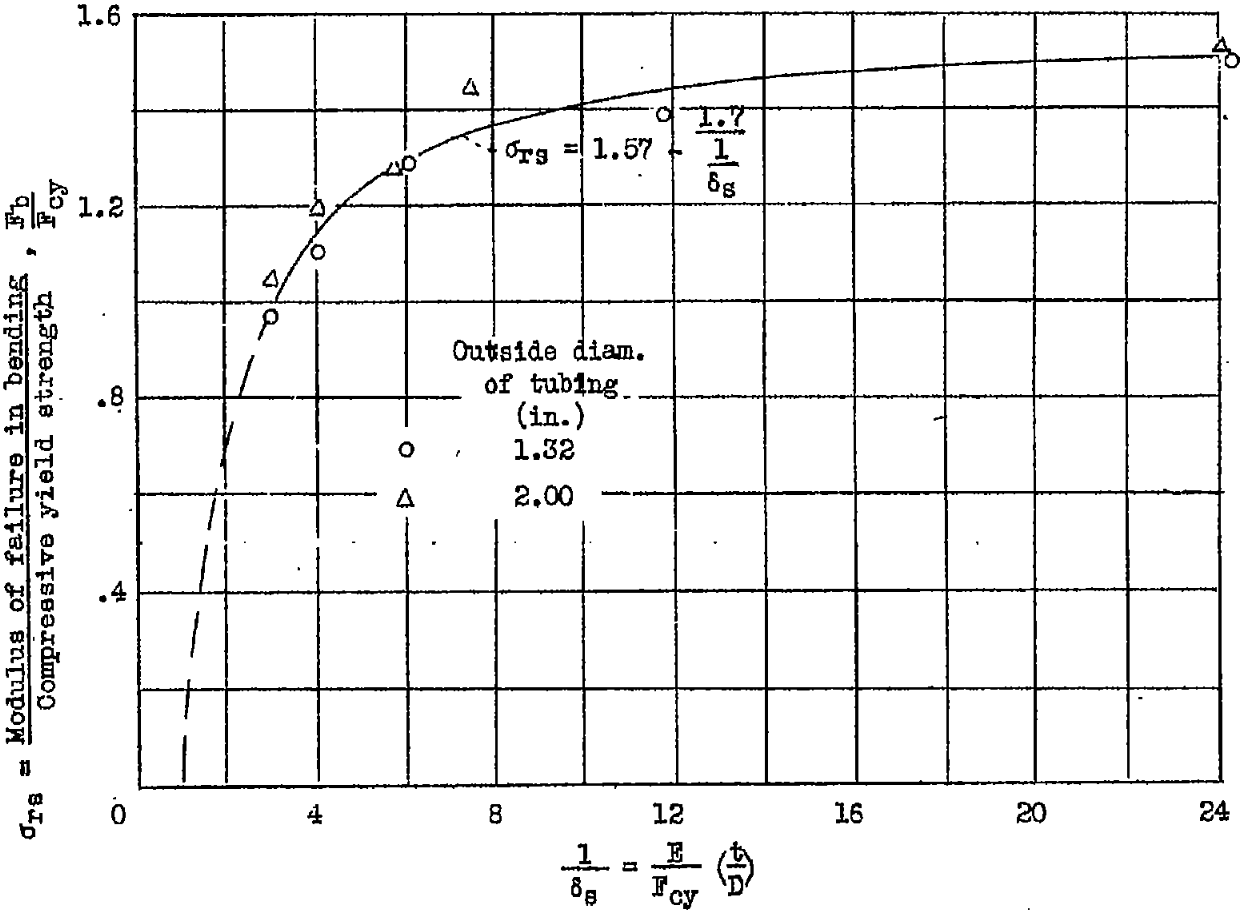

Figure 3.- Modulus of failure data from beam tests.

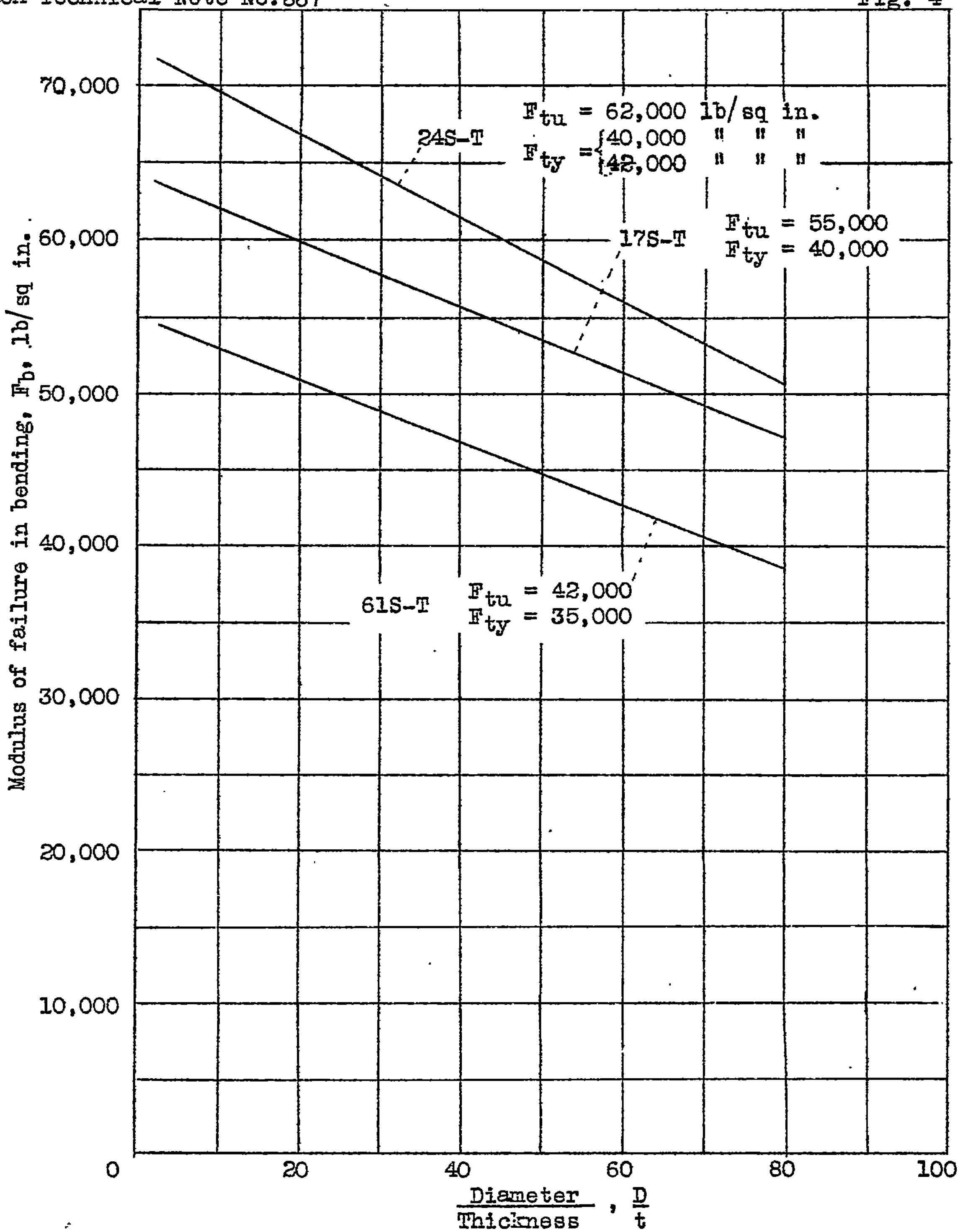

Figure 4.- Modulus of failure in bending of aluminum-alloy round tubing. Beams loaded at one-third points of span; tubes supported against local failure at loading points. (Data for 17S-T and 24S-T tubing are taken from fig. 5-6 of reference 1.)

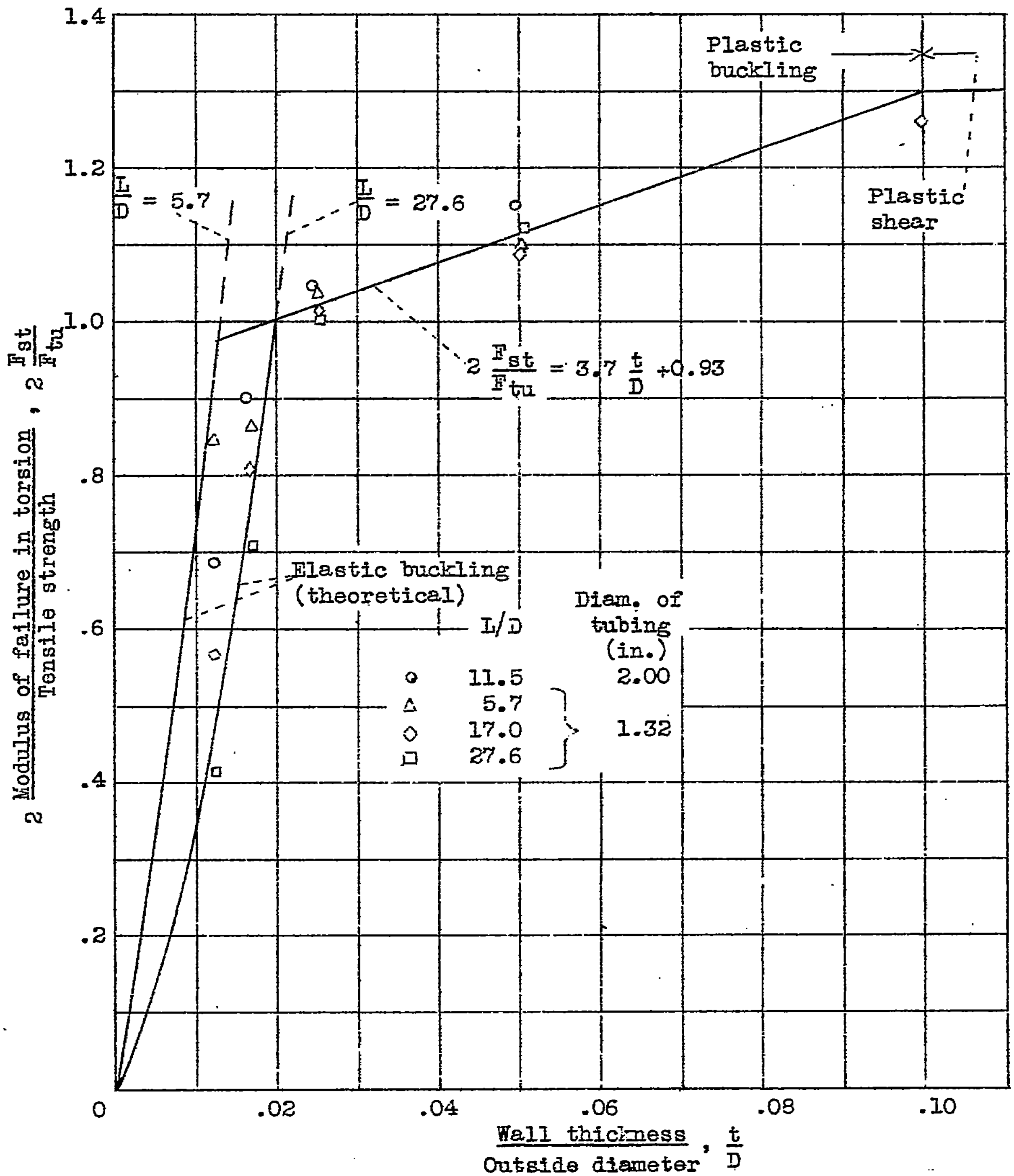

Figure 5.- Modulus of failure in torsion for aluminum-alloy round tubing.

$\frac{F_{ty}}{F_{tu}} = 0.89$ $\qquad$ F_{tu} = 44,700 pounds per square inch

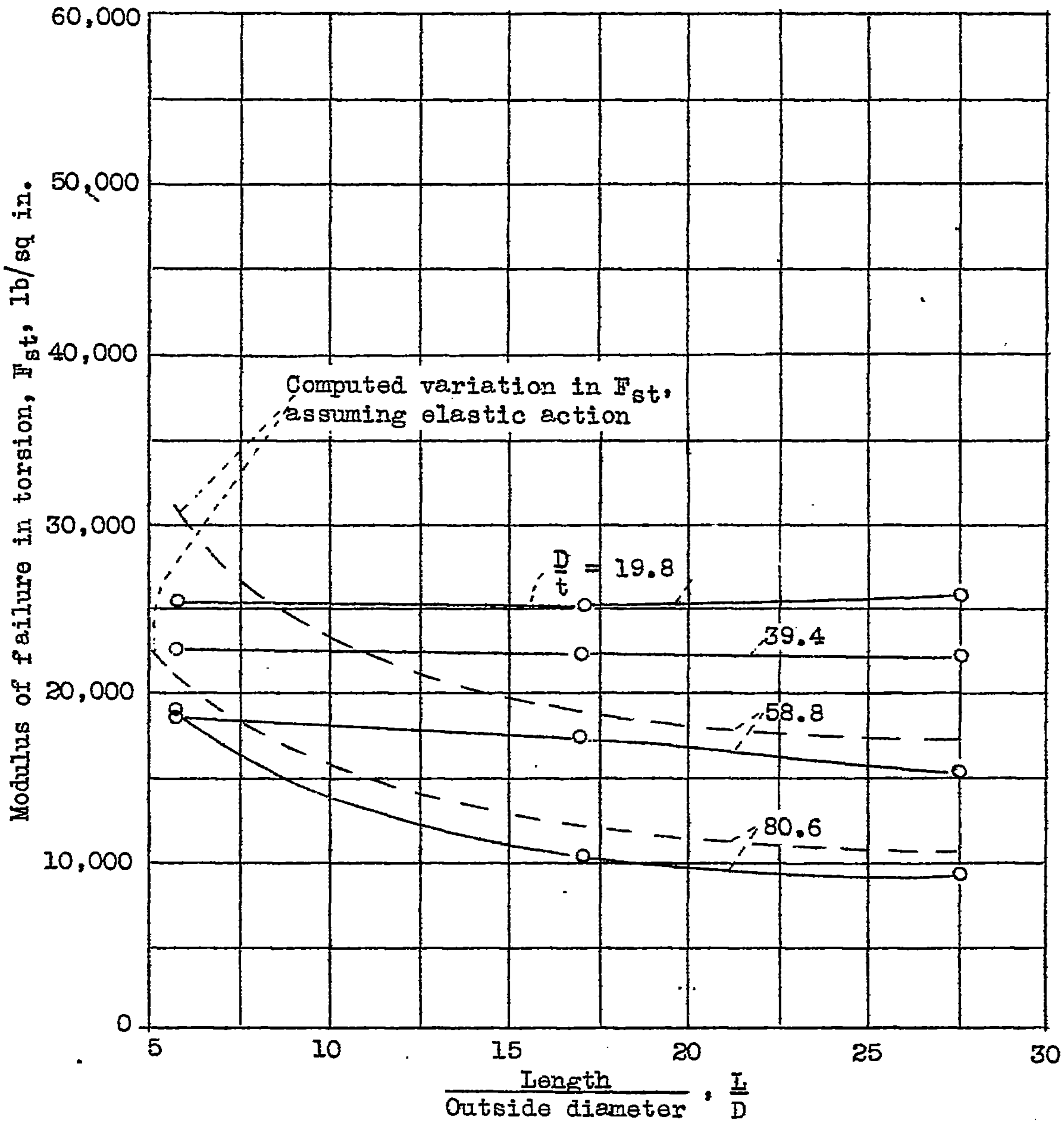

Figure 6.- Moduli of failure in torsion against L/D ratios for aluminum-alloy round tubing. Diameter, 1.32 in.

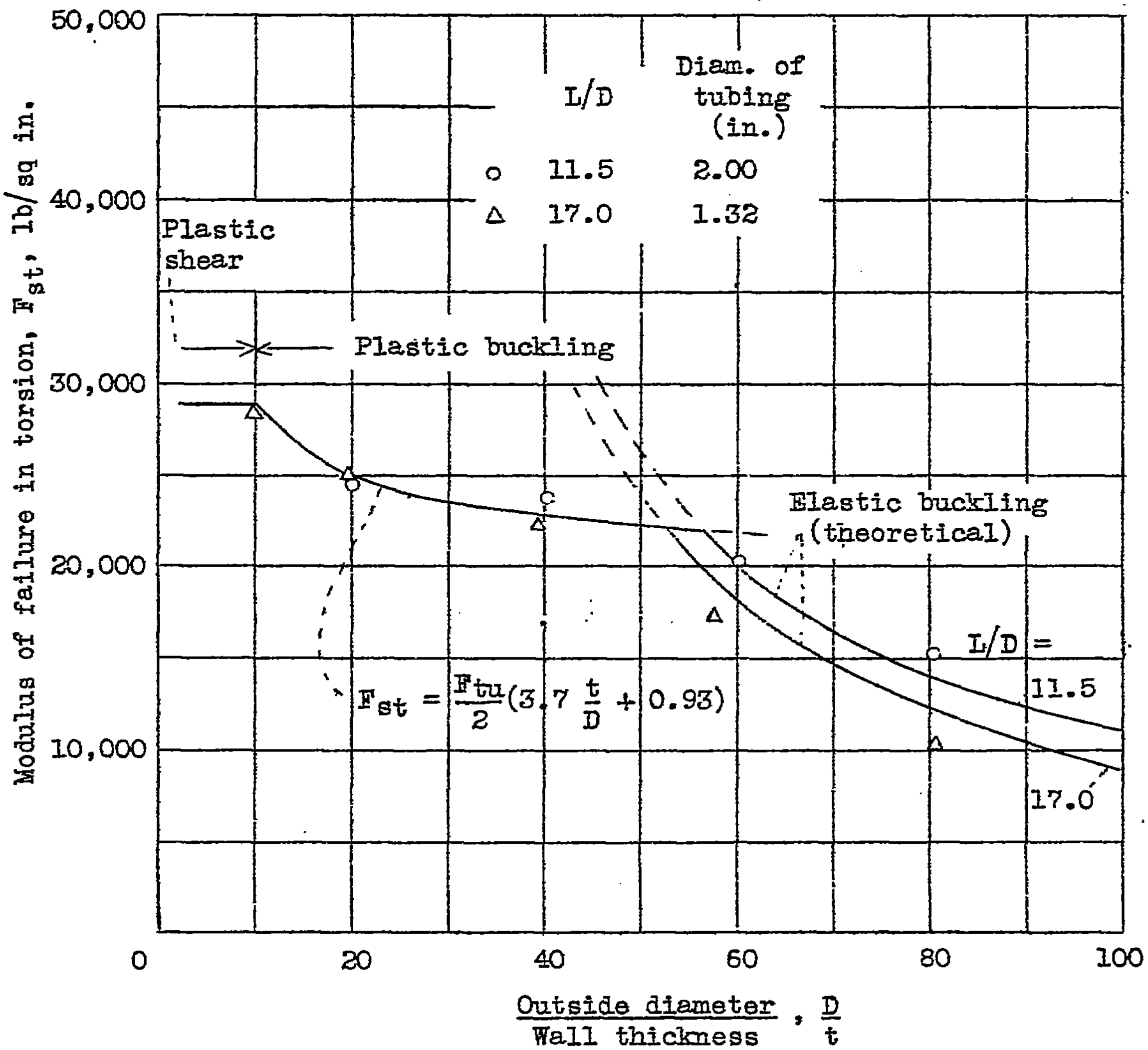

Figure 7.- Moduli of failure in torsion against D/t ratios for aluminum-alloy round tubing.
F_{tu} = 44,700 pounds per square inch

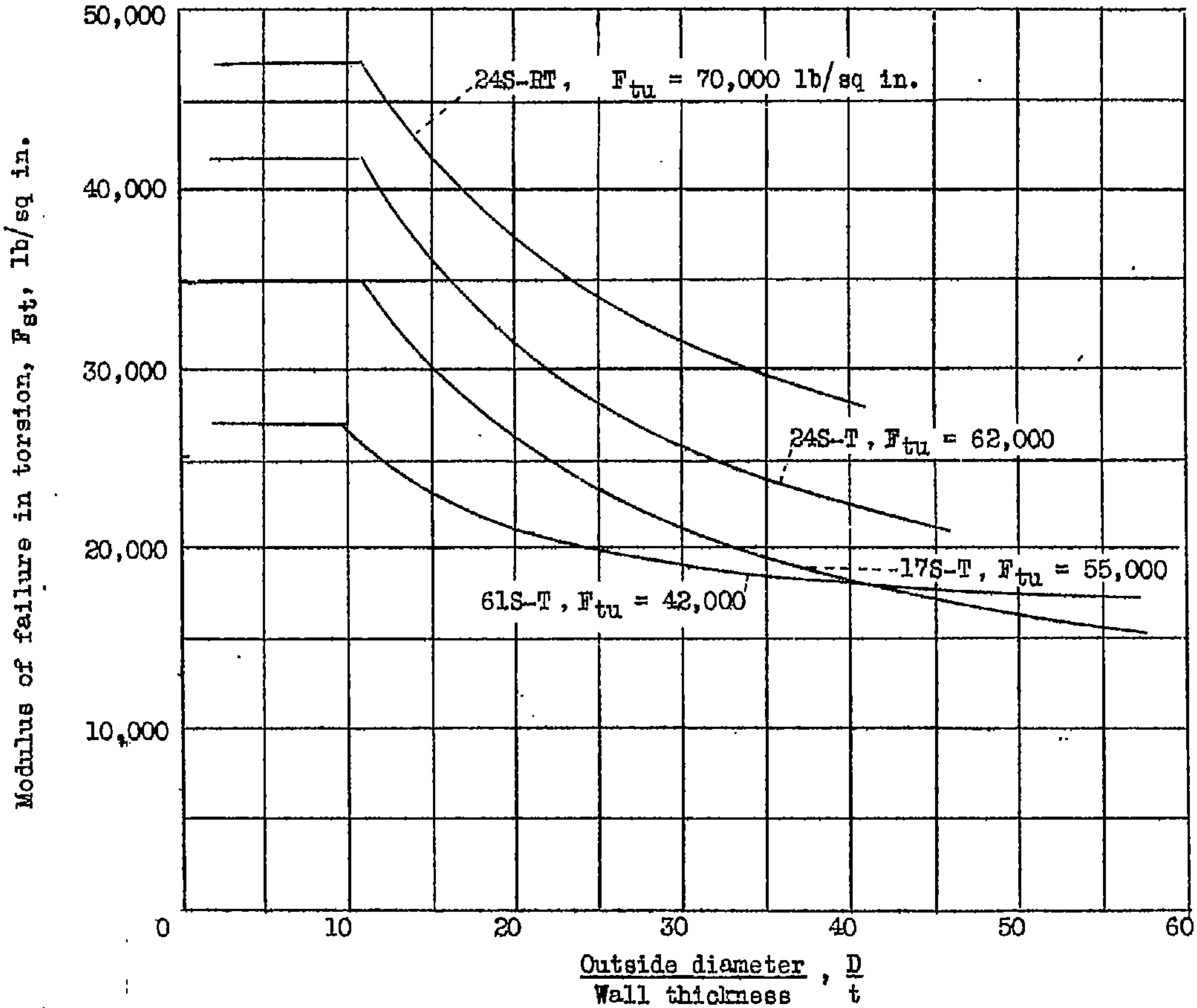

Figure 8.- Moduli of failure in torsion against D/t ratios for aluminum-alloy round tubing. (Curves for 24S-RT, 24S-T, and 17S-T tubings are taken from fig. 5-7 of ref. 1.)